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Full-Scale Tests of Lightweight Fragment Barriers on Commercial Aircraft

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16. Abstract

Because fragments from in-flight engine failures can damage critical aircraft components and produce catastrophic consequences, the Federal Aviation Administration is sponsoring research to mitigate the effects of uncontained engine bursts. SRI International is evaluating the ballistic effectiveness of fabric structures made from advanced polymers and developing a computational ability to design fragment barriers. In this reporting period, SRI performed full-scale fabric barrier tests on an aircraft fuselage at the Navy Air Warfare Center in China Lake, CA. The tests examined the effects of polymer material, number of plies, location of the fabric within the fuselage wall, and gripping arrangements.

The results were very encouraging. For example, three plies of polybenzoxazole (PBO) Zylon woven fabric glued to the outboard side of the insulation packet and weighing only 0.05 g/cm^2 (0.1 lb/ft^2) prevented a 166-g (0.37-lb) sharp-edged fan blade fragment impacting edge-on at 230 m/s (756 ft/s) from penetrating into the cabin. The absorbed energy of 4400 joules (3250 ft-lb) is nearly an order of magnitude greater than that absorbed by the unfortified fuselage wall. The results confirmed that high-strength polymer fabrics offer an extremely effective, low-weight solution for mitigating the effects of uncontained turbine engine fragments on commercial aircraft.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Because fragments from in-flight engine failures can damage critical aircraft components and produce catastrophic consequences, the Federal Aviation Administration is sponsoring research to mitigate the effects of uncontained engine bursts. SRI International is evaluating the ballistic effectiveness of fabric structures made from advanced polymers and developing a computational ability to design fragment barriers. In this reporting period, SRI performed full-scale fabric barrier tests on an aircraft fuselage at the Navy Air Warfare Center in China Lake, CA. The tests examined the effects of polymer material, number of plies, location of the fabric within the fuselage wall, and gripping arrangements.

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INTRODUCTION

Catastrophic civil aircraft accidents have occurred when fragments from in-flight engine failures damaged critical aircraft components. To reduce the probability of such incidents in the future, the Federal Aviation Administration (FAA) is sponsoring research to develop and apply advanced technologies and methods for mitigating the effects of uncontained engine bursts.

In support of this FAA objective, SRI International is conducting a research program to evaluate the ballistic effectiveness of fabric structures made from advanced polymers and to develop a computational ability to design fragment barriers. This progress report describes full-scale tests conducted during the six-month period ending 30 June 1999.

BACKGROUND

The impact tests performed earlier in this program showed that fabrics made from high-strength polymer yarns absorbed significant energy when the fabrics were firmly gripped along the edges. Aramids (Kevlar) and ultrahigh molecular weight (UHMW) polyethylenes (Spectra), for example, absorbed 6 to 7 times as much energy as aluminum alloy fuselage skin on an equal areal density basis, while polybenzoxazole (PBO) fiber (Zylon) absorbed 13 times as much energy. Such fabrics are therefore attractive as components of barriers to shield critical aircraft systems from engine debris on a commercial aircraft.

However, the weight advantage of these fabrics would be compromised by the weight of a rigid frame if the fabrics had to be firmly gripped. To investigate the effectiveness of alternative gripping methods, a series of full-scale tests was conducted in which the fabrics were attached with glue to components of the existing fuselage wall structure.

This brief report describes these tests and presents the results.

TEST METHOD AND FRAGMENT BARRIER ARRANGEMENT

Two types of titanium alloy fragments were used: a 25-g (0.055-lb) blunt-edged fragment simulator (FS), with dimensions 0.25 x 1 x 1.38 in., like those used in previous tests and a sharp-edged fragment with dimensions 0.22 x 3.0 by about 4 in. and weighing about 160-g (0.35-lb) cut from an actual fan blade (FB). The FS tests were for comparison with previous small-scale tests on gripped fabric performed at SRI, while the FB tests were for comparison with previous large-scale tests on gripped fabric at China Lake and to assess the effectiveness of different barrier attachment schemes in realistic engine fragment scenarios.

The fragments were accelerated with a 6-in. bore gas gun against an aircraft fuselage section at the NAWC–China Lake test facility (see figure 1). The fuselage was mounted on a structure that could rotate the fuselage about its axis and translate it along its axis, to precisely site the impact. The impact locations were chosen to avoid fuselage frames (see figure 2).

The fragment orientation and velocity at impact were obtained from the images recorded by two high-speed cameras mounted outside the fuselage. To investigate the worst-case scenario for preventing penetration, the fragments were intended to hit end-on. A third camera inside the fuselage recorded the damage produced in the interior wall panel and the motion of fragments that penetrated into the cabin.

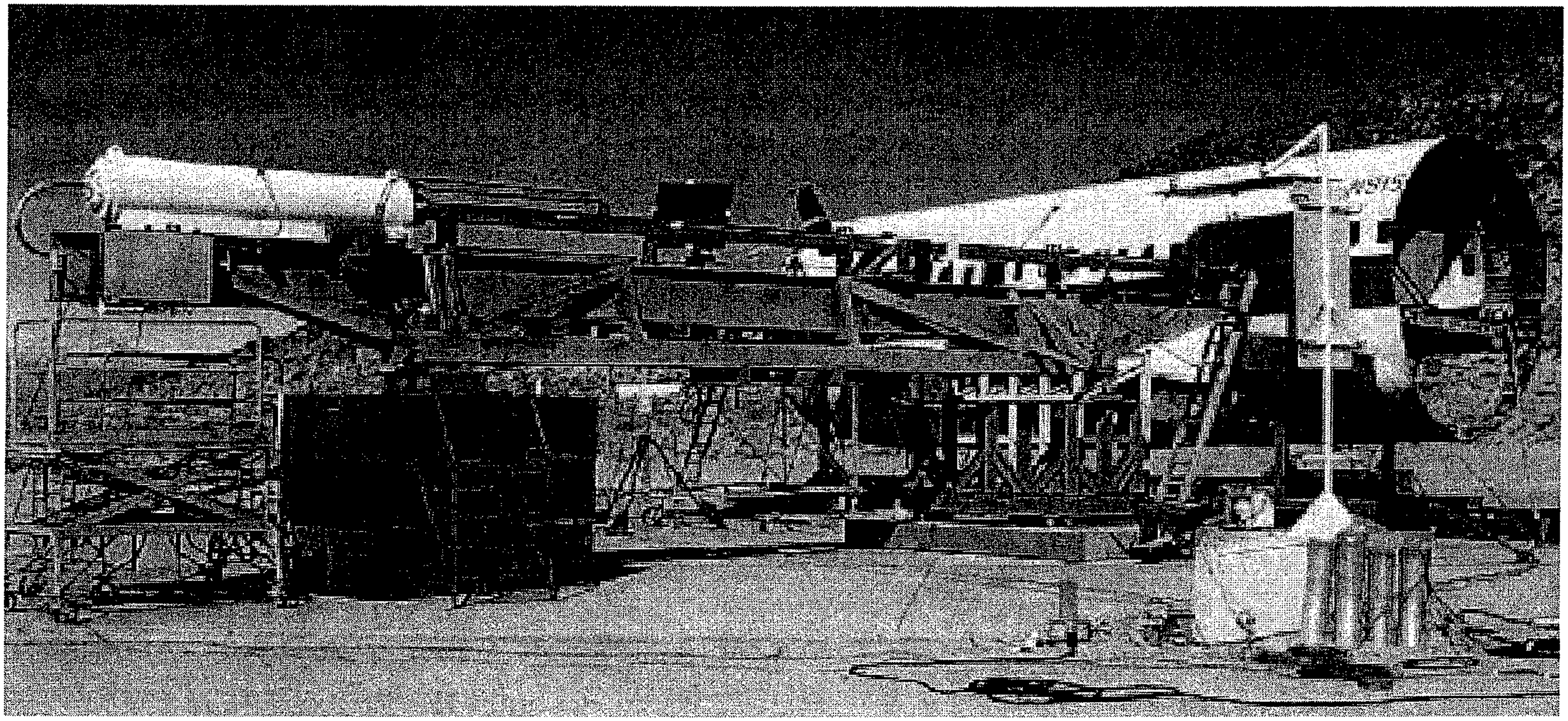


FIGURE 1. SIX-INCH BORE GAS GUN AND AIRCRAFT FUSELAGE SECTION AT CHINA LAKE FOR EVALUATING ENGINE FRAGMENT BARRIERS

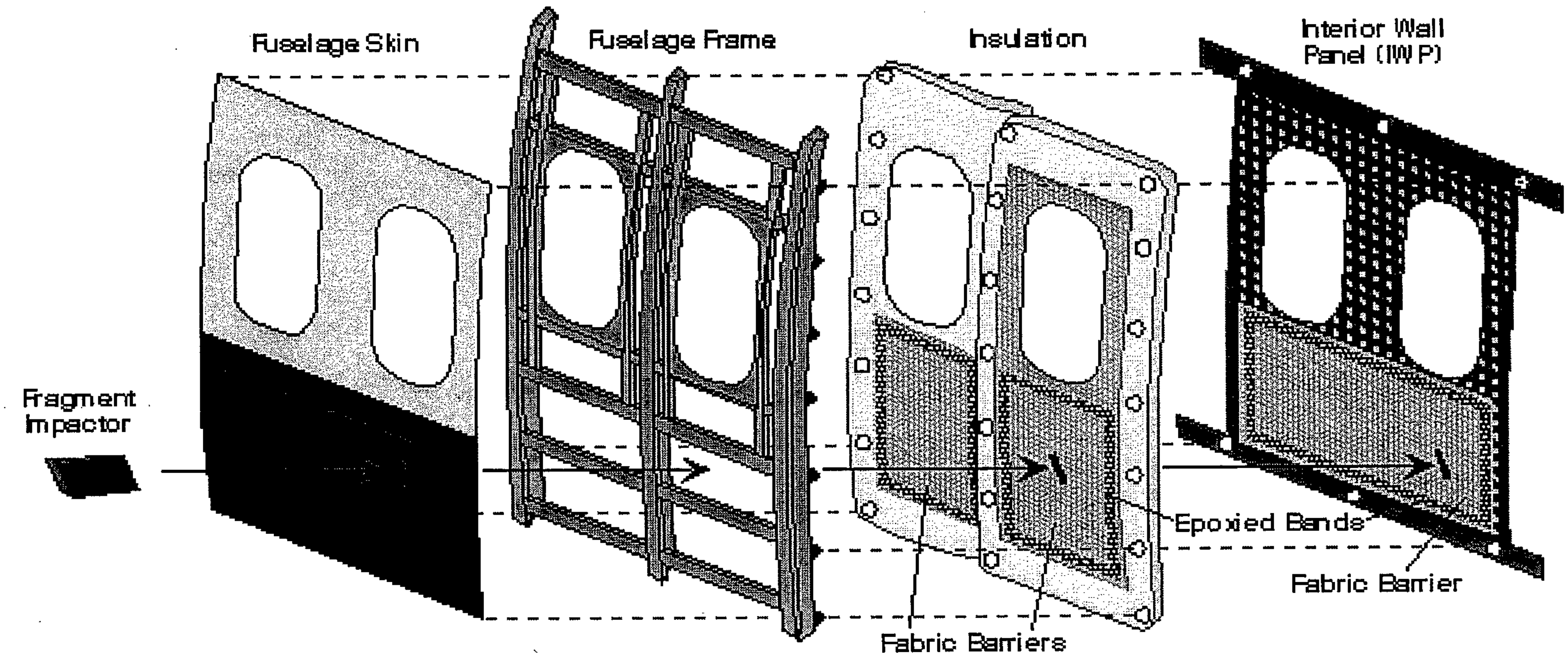


FIGURE 2. EXPLODED VIEW OF FUSELAGE WALL SHOWING LOCATIONS OF FABRIC FRAGMENT BARRIERS

The exploded view of the fuselage wall, figure 2, shows the locations of the ballistic fabric with respect to the aluminum fuselage skin, the insulation packet, and the interior wall panel (IWP). The fabric was attached with glue around its periphery either to the outboard side of the insulation or the outboard side of the IWP, or both. Previous small-scale experiments showed that gluing the fabric only around the edges not only reduced weight compared to gluing down the whole fabric, but enhanced energy absorption. Up to three fabric plies were attached to the insulation packet, and for some tests, an additional ply was attached to the IWP. The Zylon 35 x 35 weave was the fabric used for most of the tests; Kevlar 32 x 32 weave and Spectra 32 x 32 weave were used in one test each.

RESULTS

Fifteen experiments were performed; the test parameters and ballistic results are shown in table 1. The two tests involving no fabric barriers (Test 38 with the FS impactor and Test 46 with the FB impactor) were used as baseline tests to determine the energy absorbed by the unfortified wall structure, i.e., the fuselage skin, insulation, and IWP. For the tests involving fragment barriers, the additional energy absorbed by the fabric was obtained by subtracting the baseline energy from the total energy absorbed.* The specific energy absorbed (SEA) by the fabric, that is, the additional kinetic energy absorbed per unit areal density of the fabric, was taken as the parameter of merit.

SMALL FRAGMENTS.

Test 38 indicated a baseline energy of 253 J (187 ft-lb) for the 25-g (0.05-lb) fragment. One layer of Zylon fabric glued around the edges to the insulation package (Test 39) increased the absorbed energy to 461 J (340 ft-lb), and two layers (Test 43) absorbed 763 J (563 ft-lb). Thus, one or two layers of Zylon fabric increased the ballistic resistance of the fuselage wall by 80% to 200% while adding only 0.016 to 0.032 g/cm^2 (0.033 to 0.066 lb/ft^2) to the weight of the fuselage wall. A test with a single layer of Spectra fabric (Test 44) showed a 38% smaller increase in energy absorption. The only test with Kevlar fabric (Test 45) involved significant impactor yaw (about 30°) and, therefore, the measured energy absorption cannot be compared.

The tests illustrated that an important additional energy absorption mechanism may operate when the fabric is glued to the insulation. When the fragment does not perforate the fabric, significant additional energy is absorbed in accelerating the insulation, tearing the insulation bag (or debonding the glue joint between the fabric and the bag), and dragging the fabric (and any insulation still attached) through the bag and the IWP.

LARGE FRAGMENTS.

Zylon fabric extracted much greater energies from the larger sharp-edged fan blade fragments. Whereas the unfortified fuselage wall structure (Test 46) absorbed 482 J (356 ft-lb) when struck by the 152-g (0.34 lb) fan blade fragment, when two layers of fabric were attached to the

*Small differences in absorbed energy arising from fuselage skin variation were taken into account in determining barrier energy.

TABLE 1. SRI FUSELAGE IMPACT TESTS AT NAWC-CHINA LAKE (March 1999)

C.L.	Fabric Barrier					Impactor			Impact			Residual			K.E. Absorbed			SEA[e]		Results
Test No.	Fabric Mat'l.	Mesh Density	# of Plies	A. D.[a] (g/cm²)	Glued to[b]:	Mass (g)	Mass (lb)	Type[c]	Velocity (f/s)	Velocity (m/s)	K.E. (J)	Velocity (f/s)	Velocity (m/s)	K. E. (J)	Total (J)	Barrier[d] (J)	Barrier[d] (ft-lb)	(kJ/ g/cm²)	(ft-lb/ lb/ft²)	
38	—	— —	—	—	—	25	0.05	FS	615	188	438	400	122	185	253	—	—	—	—	Penetration
39	Zylon	35 x 35	1	0.016	Insul.	25	0.05	FS	631	192	461	0	0	0	461	182	134	≥11.5	≥4.1	No Pen. - Zylon-encased FS part way thru IWP
40	Zylon	35 x 35	1	0.016	IWP	25	0.05	FS	615	188	438	259	79	78	360	286	211	18.1	6.5	Penetration - perforated fabric
42	Zylon	35 x 35	1	0.016	Insul.	25	0.05	FS	797	243	735	616	188	439	296	164	121	10.4	3.7	Penetration - perforated fabric
43	Zylon	35 x 35	2	0.032	Insul.	25	0.05	FS	812	248	763	0	0	0	763	484	357	≥15.3	≥5.5	No Pen. - Zylon-encased FS part way thru IWP
44	Spectra	32 x 32	1	0.011	Insul.	25	0.05	FS	614	187	436	276	84	88	348	43	32	4.0	1.4	Penetration - perforated fabric
45	Kevlar	32 x 32	1	0.011	Insul.	25	0.06	FS	601	183	420	0	0	0	420	146	108	≥12.9	≥4.7	No Pen.- large yaw (≈30°) recorded at impact
46	—	— —	—	—	—	152	0.34	FB	647	197	2959	592	180	2477	482	—	—	—	—	Penetration
47	Zylon	35 x 35	2	0.032	Insul.	166	0.37	FB	634	193	3101	419	128	1354	1747	1235	911	39	14.1	Penetration - Perforated fabric
48	Zylon	35 x 35	3	0.047	Insul.	158	0.35	FB	634	193	2946	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	Penetration - FB escaped past fabric edge
49	Zylon	35 x 35	2	0.032	Insul.	152	0.34	FB	520	159	1914	214	65	324	1590	1168	862	37	13.3	Penetration - FB escaped past fabric edge
50	Zylon	35 x 35	3	0.047	Insul.[f]	166	0.37	FB	622	190	2985	0	0	0	2985	2503	1846	≥52.8	≥19.0	No Pen. - FB encased in Zylon attached to IWP
51	Zylon Zylon	35 x 35 35 x 35	3 1	0.063 ↑	Insul. IWP	158	0.35	FB	619	189	2808	0	0	0	2808	2877	2122	≥45.5	≥16.4	No Pen. - FB encased in Zylon attached to IWP
52	Zylon	35 x 35	3	0.047	Insul.[f]	166	0.37	FB	756	230	4409	0	0	0	4409	4418	3259	≥93.2	≥33.6	No Pen. – FB encased in Zylon attached to IWP
53	Zylon Zylon	35 x 35 35 x 35	3 1	0.063 ↑	Insul. IWP	158	0.35	FB	804	245	4738	0	0	0	4738	4456	3287	71	25.4	Penetration – FB (encased in Zylon) exits IWP with negligible velocity

[a] Areal density.

[b] IWP is interior wall panel.

[c] FS (fragment simulator) is blunt-edged, with dimensions 0.25 x 1 x 1.38 in. FB (fan blade fragment) is sharp-edged, with dimensions 0.22 x 3.0 by ≈4 in.

[d] Difference in kinetic energy absorbed between this test (with the fabric barrier) and corresponding test (FS impactor: Test 38, or FB impactor: Test 46) without a barrier, with corrections included for difference in the fuselage wall thickness (based upon China Lake impact test data): 20 J (15 ft-lb)/0.001 in. increase in fuselage skin thickness for sharp-edged FB impactor (with negligible yaw and pitch); 10.5 J (7.7 ft-lb)/0.001 in. increase for blunt-edged FS impactor.

[e] Additional K.E. absorbed divided by areal density of the fabric barrier (SEA in ft-lb/lb/ft² = 0.74 X SEA in J/g/cm²). For tests with no penetration, the SEA is a lower bound.

[f] Fabric is glued to two adjacent insulation panels.

insulation package (Tests 47 and 49) an average of 1670 joules (1230 ft-lb) were absorbed (an increase of 350%). When fortified with three layers (Tests 50 and 52) the wall absorbed up to 4400 J (3200 ft-lb), an increase of 800%, and when three fabric layers plus a layer on the IWP were installed (Tests 51 and 53), up to 4700 additional joules (3500 ft-lb) were absorbed, an order of magnitude more than absorbed by the unfortified fuselage wall. In Test 53, a barrier consisting of three plies of Zylon, 35 x 35, glued to the insulation and a single layer on the IWP defeated a 158-g (0.35 lb) sharp-edged fan blade fragment impacting end-on at 245 m/s (804 ft/s). This is a very impressive increase in energy absorption of • 4.45 kJ (• 3300 ft-lb) for an areal density increase of only 0.063 g/cm^2 (0.13 lb/ft^2).

Figures 3 and 4 show photographs of the fragment, fuselage skin, and IWP for Test 39 with the small fragment and Test 50 with the fan blade fragment. In these two tests, the fragment was unable to completely perforate the fabric layers. The fabric-cloaked fragment broke through the IWP, but was arrested there. This fragment "capture" mechanism has important implications in designing lightweight barriers, as discussed below.

A comparison of two tests with three layers of Zylon glued to the insulation (Test 51 with an additional layer glued to the IWP and Test 50 without the additional layer) shows that the additional layer on the IWP prevents the fragment from protruding as far through the IWP. However, since both barriers arrested the fragment, the tests did not establish whether an additional ply glued to the insulation would be more effective than the additional ply glued to the IWP.

DISCUSSION

Comparing the full-scale experiments to the laboratory tests demonstrated that fabric barriers absorb more energy if the fabric is not firmly gripped and can be pulled along by the fragment. For both the small and large fragments, gluing the fabric to the insulation and/or the IWP resulted in much greater SEAs than obtained in laboratory tests in which the fabrics were tightly gripped. This finding is consistent with earlier small-scale gas gun tests that showed higher energy absorption for fabric gripped on two sides than gripped on four sides.

The unfortified wall structure of the fuselage offers little resistance to an impacting fragment. The fragment penetrates by a low-energy punch-through mechanism, engaging little more material than that under its footprint. Comparing Tests 38 and 46, it is seen that the smaller FS fragment penetrated the fuselage wall with roughly half the energy loss as the large FB fragment, consistent with the relative sizes of their footprints* and sharpness of their leading edges.

Because of their high strength-to-density property and their ability to "give" during impact and spread the load, the ballistic fabrics substantially increase the energy absorption when inserted in the fuselage wall, even when they are cut by the fragment, i.e., even in the punch-through mode. However, a much greater absorbed energy benefit can be realized by circumventing the punch-through mode.

*The FB has a footprint area 2.64 times that of the FS (at zero yaw and pitch) and lost 1.9 times as much energy as the FS in penetrating the unfortified fuselage wall structure.

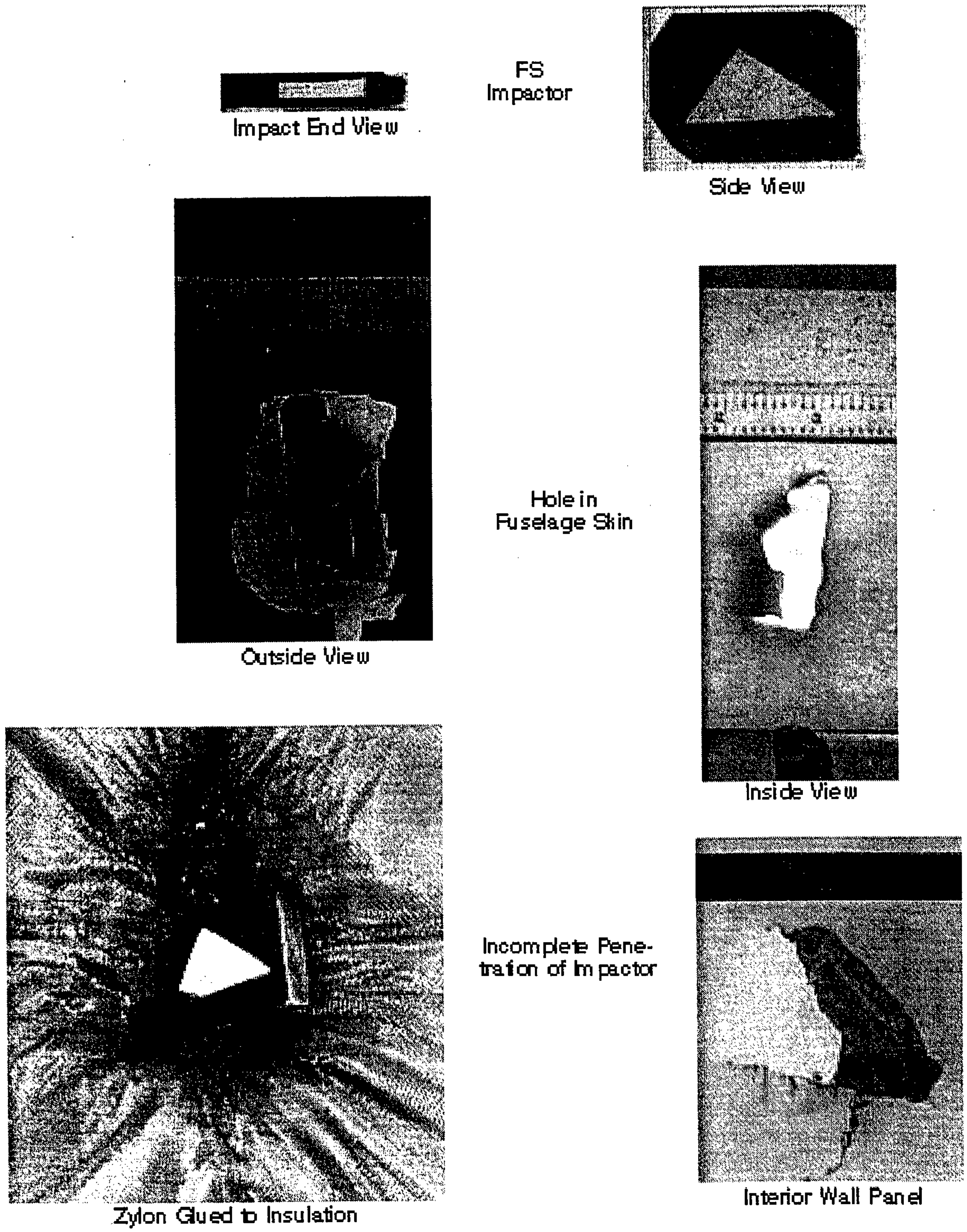
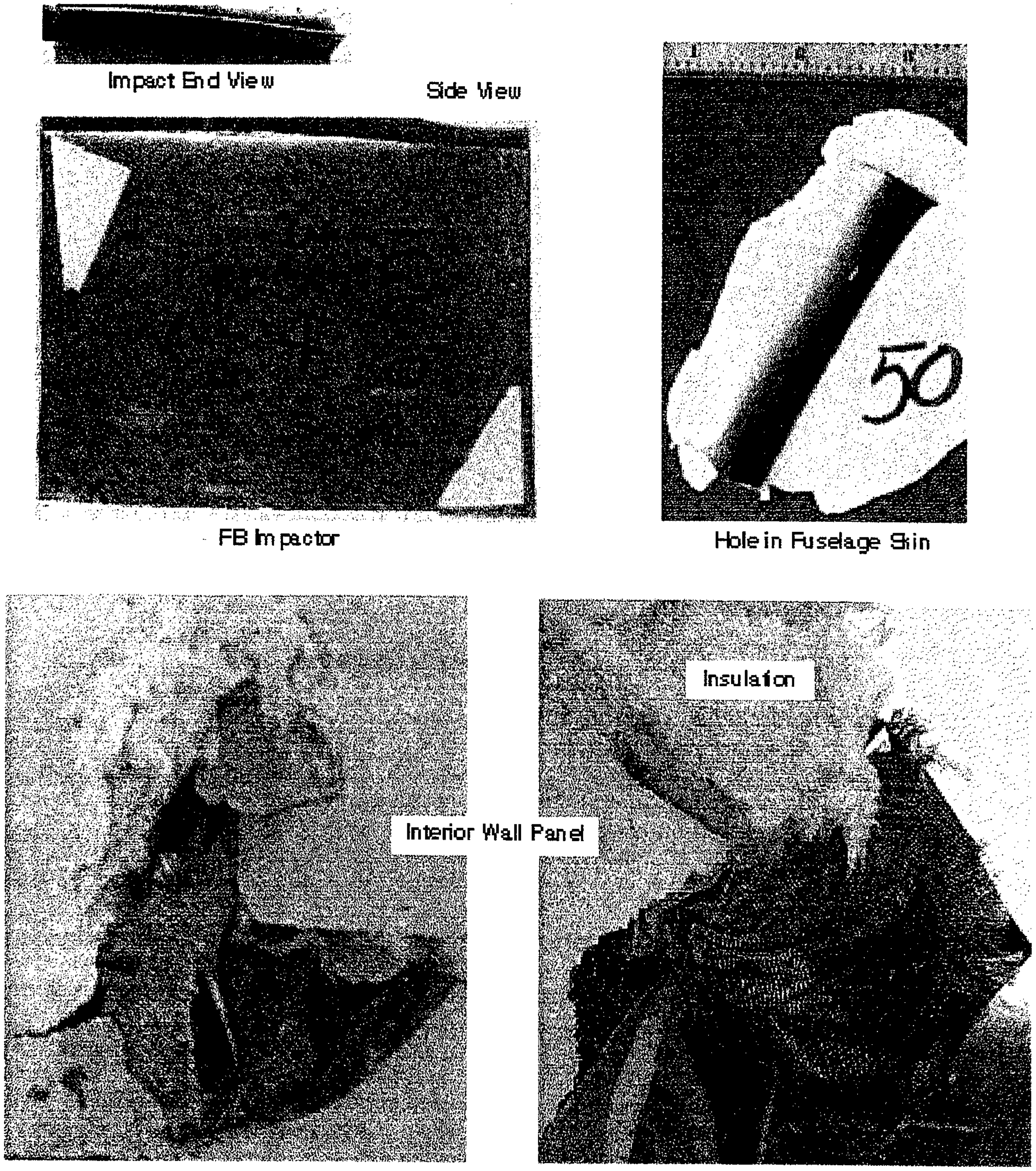


FIGURE 3. POSTTEST PHOTOS FROM TEST 39
(25-g (0.555 lb) blunt-edged fragment simulator (FS) at 192 m/s (631 f/s)
1-ply Zylon 35 x 35 fragment barrier glued to insulation.)



Incomplete Penetration of Impactor

FIGURE 4. POSTTEST PHOTOS FROM TEST 50
(166-g (0.37 lb) sharp-edged fan blade fragment (FB) at 190 m/s (622 f/s)
3-ply Zylon 35 x 35 fragment barrier glued to insulation.)

If the fabric is not cut, but instead cloaks the fragment, the fabric layer(s) and everything attached (insulation bag, for example) are carried forward by the fragment, adding considerable mass and drag, especially as material is pulled through the hole in the wall panel. Using multiple fabric layers improves the resistance to punch-through (cutting). Tests 47 through 53 show that two to four layers of Zylon can prevent a large sharp fragment from cutting through the fabric and result in a very large SEA.

CONCLUSIONS

These results and observations lead to the following conclusions

- High-strength polymer fabrics are weight-efficient barriers to uncontained engine fragments when attached within the fuselage wall of a commercial aircraft
- Gluing the fabric around its edges to the outboard side of the insulation package or the interior wall panel is an effective and practical way to implement the fabric in an aircraft.
- Suppressing the punch-through penetration mode greatly enhances the ballistic benefit of a fabric.
- Multiple layers of ballistic fabrics resist fragment punch-though and result in significantly higher specific energy absorption.
- Cut resistance may be an important fabric property for fragment barriers.

FUTURE WORK

Further tests are needed to more firmly establish the energy absorption levels for the various fragment-into-barrier scenarios and to provide data for further development, calibration, and verification of SRI's computational fabric model. Parametric results from independently and systematically varying fragment mass, cross-sectional area, and impact edge sharpness; impactor orientation and impact obliquity; and fabric barrier material and number of plies will be efficiently obtained with the 6-in. gas gun at SRI's remote test facility and validated by full-scale tests at China Lake.

Other methods of attaching the ballistic fabrics to the aircraft structure should be investigated. For example, incorporating the fabric inside the moisture-proof lining of the insulation bag and/or extending the fabric beyond the reinforced holes in the bag and fastening it around the frame protrusions* may offer additional benefits in ease of installation and ballistic protection. The cut resistance of various fabric materials should be measured.

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*In Tests 48 and 49, the fragment impacted the fabric barrier close to its edge and eventually penetrated into the cabin, not by perforating the fabric, but by escaping around the fabric edge. Extending the fabric barrier to the edges of the insulation bag could prevent this.